

Founding Father

Paul Baran conceived the Internet's architecture at the height of the Cold War. Forty years later, he says the Net's biggest threat wasn't the USSR - it was the phone company.

By Stewart Brand

In 1961, at the height of the Cold War, an engineer named Paul Baran sold the US Department of Defense on the idea of a failure-resistant communications method called packet switching. But because of roadblocks at AT&T and the Pentagon, it wasn't until the 1970s that the technology was finally adopted as the foundation architecture of the Arpanet - the precursor to the Internet.

In April, Baran (pronounced "BEAR-en") will receive the Franklin Institute's 2001 Bower Award and Prize for Achievement in Science, his latest in a string of prestigious honors from professional organizations including the Institute of Electrical and Electronic Engineers (IEEE), the Association for Computing Machinery (ACM), and NEC. Over a lifetime of quietly sustained achievement as inventor and entrepreneur, Baran cofounded the Institute for the Future and created a series of successful companies - Cabledata Associates, Packet Technologies, Metricom, Interfax, and Com21 - based on technologies he developed. As corporations like Cisco acquired his businesses, Baran's inventions went mainstream: His discrete multitone technology is at the heart of DSL, and his developments in spread spectrum transmission are essential to the ongoing wireless explosion. Yet Baran is little known outside his field.

For this rare interview, I chatted with Baran in his meticulously tidy home office in Atherton, California. Aside from the glint in his eye, there is nothing hackerish about Baran. He comes across as a consummate professional: modest, formal, and, at 74, as sharp and engaged as ever.

Baran is greatly concerned about getting the history of technology right. He took the trouble to check over the transcript of our interview with details from documents published between 1959 and 1965, a period when thousands of intercontinental ballistic missiles were poised to end civilization.

Wired: The myth of the Arpanet - which still persists - is that it was developed to withstand nuclear strikes. That's wrong, isn't it?

Paul Baran: Yes. Bob Taylor¹ had a couple of computer terminals speaking to different machines, and his idea was to have some way of having a terminal speak to any of them and have a network. That's really the origin of the Arpanet. The method used to connect things together was an open issue for a time.

Which Taylor heard about not through you, but through Donald Davies² originally?

I have two different views on that. I didn't pay much attention to it then, but with all the nonsense about it, I went back and started digging through the old records. I don't believe anything unless I can find it in writing, in contemporaneous documentation. I had many, many discussions with the folks at Arpa, starting in the very early '60s. The information about packet switching³ was not a surprise, not new. People can listen to things and put them in the back of their mind. So you don't know. People say they'd never heard of me at the time, yet I'd chaired a session with them in it.

It's a beautiful exercise in the fallibility of leaky memories and why you want to build a library to last 10,000 years. I'm now a trustee of the IEEE History Center. I think we're underinvesting in

recording history. Look at the crazy economy we have right now, and all the growth and productivity - which we do not understand - with Alan Greenspan saying it'll be 10 years before we know whether we have a different economy or it was just a bubble. And we're not even recording the key facts. Lawyers are asking companies to destroy all records after three months, lest some sleazeball lawyer play games with discovery. We're in a period where key records are being destroyed very quickly, and some very important issues on what the hell is happening today we won't even be able to unravel.

I didn't know about Davies until he independently came up with the same idea. He visited Rand⁴ while I was there, but he's probably the only guy who didn't get a presentation on this. I don't know the reason - I probably was out of town. He was an honest guy, and I'm sure it was done independently. But the origin of packet switching itself is very much Cold War.

The argument was: To have a credible defense, you had to be able to withstand an attack and at least be able to show you had the capability to return the favor in kind. Now whether it would ever be done or not, God knows not. But you had to be able to do that, and that was a limitation on the second-strike capability.

The second-strike capability was under discussion, and you were involved in that when?

I did this stuff at Rand around 1960. I had joined Rand in '59. But beware of anybody whose history of the subject starts the day they entered the field. You always build on previous work. As I understood the issue then, it was to be able to get the signal of "go" or "no-go" out to the missiles.

But you had already worked on the Minuteman⁵ intercontinental missile.

Yes, this was back at Hughes.⁶ That was '55 to '59.

In 1955 you were 29, and you were an engineer - working on what?

I joined Hughes to work with the Systems Group on what we called the Vest Pocket SAGE.⁷ You know, the SAGE system was a big, big monstrous thing. Then transistors arrived, making it possible to build the whole thing inside a van. That's what Hughes was doing. They did the first one for the Army and the second one for the Navy. It became the Navy's tactical data system.

This was all missile detection?

No, this was for airplane detection. The very early missiles took all day to fuel up, so you had warning time to do something. But when missiles went from liquid fuel to solid-state,⁸ the danger increased tremendously.

When did the solid-state missiles come in?

It depends on which stage. The first discussions were early '50s. They actually didn't come out till a couple years later. When Kennedy ran for office in 1960, he made an issue of this missile gap - which, after the fact, turned out to be bullshit.

Do we know if he knew it was bullshit?

I think so. It was very closely held, but I think Eisenhower gave him briefings.

So he could pretend it was a problem and the administration couldn't really deny it without blowing what it did know.

That's right. But I didn't learn about this till much later. Back then I was going under the assumption that there really was a missile gap. The real proof of what was happening came later in the early '60s, when U-2 spy planes brought back information that they couldn't find the Soviet missile sites.

Anyway, I was over at Hughes in the late '50s. They were bidding on a contract for the design of the Minuteman control system. I was scared shitless, because you had all these missiles that could go off by anyone's stupidity. The technology was never to be trusted.

Were your coworkers similarly worried?

Absolutely. We knew it was the most dangerous thing ever put together. The people who were working on these problems at the time were all scared stiff of what might happen if we did nothing. It's about as nasty a problem as has ever confronted the world. We thought, What can we do to reduce its likelihood?

In all my time at Rand and dealing with the DOD, I never heard anyone ever express any desire whatsoever for thermonuclear war, knowing how destructive it would be for all civilization. I dug up my old Rand bomb damage calculator⁹ as a reminder of those times. Notice that this device, which provides the magnitude of the damage anticipated in a nuclear strike, is unclassified. Those who understand how wars are started, and the scale of the destructive force of nuclear weapons in reality, hold views totally opposite to scientists portrayed in *Dr. Strangelove*. I got very interested in the subject of how the hell you build a reliable command and control system.

And they said, "Go ahead, kid," or what?

No single person ever does anything. It's always groups of people. We wanted to know how to go about building such a system. So I got interested in the subject of neural nets. Warren McCulloch¹⁰ in particular inspired me. He described how he could excise a part of the brain, and the function in that part would move over to another part. As we get older - at least this was thought in those days - the number of brain cells decreases but we're able to use the surviving functionality effectively. As you and I are getting older, we know it takes a little time to remember a word - so we find a synonym. We have more trouble with proper nouns because there's lower redundancy. McCulloch's version of the brain had the characteristics I felt would be important in designing a really reliable communication system. As I worked on the communication problem, I felt that I could do better at Rand. They had more freedom than at Hughes.

Give me a little picture of Rand. There are whole books about Xerox PARC, but I haven't seen much on Rand. Was it brilliant leadership, a brilliant system? What made it work?

All of the above. Great leadership, great researchers, and great freedom to be effective. Its first president, who served for many years, was Frank Collbohm, a former test pilot. Frank was a very smart and understated man who went to great lengths to avoid taking any limelight away from the staff. As an example of the policies, the only person allowed to deliver a presentation was the researcher who actually did the work.

The original building was two stories and had courtyards. It was designed by a mathematician, John Williams, who figured out the greatest chance of taking different paths to get from point A to point B, so you had more random encounters with other people.

It worked. It's very difficult to get people with such different skills - physics, social sciences - to connect. But Rand was the most productive damned place I've ever seen.

So there you were at Rand - it's '59, '60 - and you were interested in command and control for ...?

I was just interested in the general subject of command and control and some of the issues. I had some very, very crude insights. Then a request came in on the issue of command and control communications for survivability. I said, "Hey, that's something I'd like to work on." The first thing I did was make sure the stuff we did at Hughes got written up. That's the freedom you had at the place. Rand allowed it to a great degree. We don't have enough trust inside the government today to allow such things.

There was another crazy thing that occurred at Rand. Somebody was doing a study on termination of wars. How the hell do wars stop? Interesting problem, but Congress got all pissed at the idea. They even passed a law forbidding government-funded defense researchers from studying surrender. They were afraid that somebody would think our study of surrender would indicate that we were exhibiting weakness. So the study of surrender continued, but you didn't call it that. We didn't emphasize that communications was important in cooling things off; we did emphasize getting the word around to go fire your missiles.

Sometimes certain terms take on a meaning of their own and become real. One was "minimum essential communications." The military said all they wanted was "minimum essential communications," and I believed them. So I thought data rate would take care of everything - get the word out, calm things down if necessary. You don't need a hell of a lot of communication for that.

So then I picked up on an idea from Frank Collbohm that the problem is the military depends heavily on high-frequency communications. A high-altitude nuclear burst takes out the ionosphere¹¹ for many hours. So the only thing that was left was the ground wave¹² - that's what you get from broadcast stations during the day in the short range. Collbohm's idea was for the radio stations to relay the message from one to the other. But there are a lot of them in the US. So I said, "Let's automate it." That would make it practical.

The first crack that I took at it in 1960, I got an old Johniac computer and a plotting board, and I plotted the locations of all the AM¹³ radio stations in the US. Yeah, there's plenty of paths; I said look at the range.

That went off in two directions.

One, I went out with a briefing chart, saying, "OK, here's the solution to your problem." I got push-back from the military: "That takes care of the president getting word to the missile, but what about me? I've got to speak to the troops. I've got to do this and that. I need more communication."

Meanwhile, the Air Force took the idea and gave it to Rome Air Development Center. They built it as a teletypewriter system and tested it. It worked just fine. And they did something cute: They used the AM radio stations, but slightly modulated their frequency - around 20 Hz. You couldn't hear it on your radio, but it let us send a frequency-modulated¹⁴ teletype signal.

Was that implemented?

Yeah. It was implemented, tested with a dozen stations, and it all worked fine. That may have been the first packet-switching system.

Let me see if I actually understand this. These were AM stations. And this system is doing frequency modulation on that, so it's turning these AM stations into secret FM stations for teletype messages of "go" and "no-go" on missiles. That's diabolical. That's pretty good.

I didn't invent that. Whoever it was at Rome did that.

Did the AM stations know this was going on?

I didn't get involved with it, but I saw a piece in an amateur radio magazine where somebody said that it was a hush-hush program at the time.

It's sort of wild. Here are radio stations, who are the ultimate blabbermouths, and you use them as your channel of extremely secret, extremely important communication.

Really, the issue was, Why don't we use the telephone system? AT&T was a total monopoly at the time.

And totally in bed with the Defense Department?

There were whispered stories about that, but I think their own interests and their own perception got the best of them; we'll get back to that. But if you had an attack - and not very many missiles - aimed at our strategic forces, it would take out the telephone system without even aiming for it. Collateral damage was the name for it, a frightening thing. That analysis was done at Rand. AT&T wouldn't give us the maps, so we got them through the back door.

That's shocking, that they wouldn't give you the maps.

They didn't want to expose their vulnerability.

To the enemy. I see.

The definition of *enemy* is still open.

That's the famous problem of secrecy. How do you solve a problem if you can't admit that you have it?

The problem was that the telephone system was centralized. You had a hierarchical switching system. It was a five-level hierarchy. You had switching centers. It was all analog transmission in those days, and you couldn't go through more than five links before the quality was unacceptable.

So you had the realization that the phone system couldn't be trusted. And the fallback, which was high-frequency radio, couldn't be trusted in a nuclear environment. So a distributed network of ground-wave transmission was one direction of solution. I tried to figure out how much communications we needed and went around to different command centers and asked them what they needed. You could just pick up and go and do all these things. Now there would be a lot of red tape. Back then Rand had a blanket "need to know," so I had no problem on that.

I figured there was no limit on the amount of communications that people thought they needed. So I figured I'd give them so much communications they wouldn't know what the hell to do with it.

Then that became the work - to build something with sufficient bandwidth so that there'd be no shortage of communications. The question was, how the hell do you build a network of very high bandwidth for the future? The first realization was that it had to be digital, because we couldn't go through the limited number of analog links.

How obvious was that in 1960?

In 1960, I did some interesting studies on redundancy and we simulated it at Rand. We built a network like a fishnet, with different degrees of redundancy. A net with the minimum number of wires to connect all the nodes together, we called 1. If it was crisscrossed with twice as many wires, that was redundancy level 2. Then 3 and 4. Then we threw an attack against it, a random attack.

A very interesting thing happened. You can build very, very tough networks - by tough I mean a high probability of being able to communicate if the two end nodes survive - if you had a redundancy level of about 3. The enemy could destroy 50, 60, 70 percent of the targets or more and it would still work. It's very robust. That was the thing that struck me.

But it was necessary to build it digitally. Analog could not repeat the signal well enough. With digital you clean up the message, so you can go through a lot of repeaters, and you reconstruct the same signal. Analog is like making a videotape of a videotape of a videotape: The quality goes to pot. We had to go through a lot of different connections, so the only way we could do it would be digital.

The phone system was analog then. In 1960, was anything digital?

Nothing. AT&T was doing some work on pulse code modulation [15](#) for what became the T1, but it was only designed for short distance, and that work went to their Bell Labs division. AT&T and Bell Labs were really two different places. The digital folks at Bell Labs understood what I was doing and were very positive and favorably inclined. It was AT&T headquarters, with the old analog people, that missed it. If a guy knew only analog, he could not comprehend what I was saying about the behavior of a digital circuit.

If you were going to build a network with redundancy, that tells you right there how many paths you need. There's no choice. At the same time, you don't have to use high-priced stuff anymore. Because in the analog days both ends of the connection had to work in tandem, and the probability of many things working in tandem without failing was so low that you had to make every part nearly perfect. But if you don't care about reliability any more, then the cost of the components goes way down.

You were trying to build a reliable system with unreliable components?

Exactly. That's the key.

It's a profound concept. One imagines it's the other way, that even with reliable components you'll probably get an unreliable system, and here you're saying, "No, actually, with unreliable components ..."

You can get any reliability you want - far, far greater than the reliability of the components. The thing I found intriguing is it did not take a lot of redundancy to do it. Just a moderate degree of redundancy, properly used, gave me this big payoff in reliability.

Was there error-checking and error-correction in this system?

That came next. One of the characteristics I laid down for myself was that we also wanted to do voice. Everything would get converted to digital: Teletype, data, and voice. If you do voice, that gives you some restrictions on minimum data rates and how long you can afford to be at any switching node, where you look at the message and pass it on. So we said, "Let's have a half-second delay maximum from one point to another." Then at every one of these nodes we would keep a carbon copy of the message until we're sure it got through intact to the next node. It was easy to spot errors, but correcting errors was difficult. So the carbon copy with error detection allowed repeated transmission of any message block, now called a packet.

A packet was a standardized block of data - it had to say who it was going to, who it came from, and how long it was in the network.

Saying a network is digital does not automatically mean it's packetized.

Oh, no. Not at all. There's a major distinction to keep in mind between message switching¹⁶ and packet switching. Donald Davies later said that he picked the name packet switching intentionally to separate it from message switching.

Anyway, you send the packet out, and when this station gets it off to the next guy, it sends back, "OK, got it. You can erase the previous one." If the first station doesn't hear back, it sends another copy out in a different direction. The packets can arrive out of order. We just sort them out at the end. Since it didn't have to be synchronous, you didn't have to lock everything all together.

It didn't take very long before we started seeing all sorts of wonderful properties in this model. The network would learn where everybody was. You could chop up the network and within half a second of real-world time it would be routing traffic again. Then we had the realization that if there's an overload in one place, traffic will move around it. So it's a lot more efficient than conventional communications. If somebody tries to hog the network, the traffic routes away from them. Packet switching had all these wonderful properties that weren't invented - they were discovered.

Did you have a lot of breakthroughs, as opposed to just grinding away at the problem?

Yeah, epiphanies. I had a whole string of them. I say they're mostly discoveries rather than inventions. Like the realization that by breaking the physical address from the logical address,¹⁷ you could move around the network and your address would follow you. There were about a dozen things like that. I'm sure there must've been a zillion false leads, but we filtered them out.

What it sounds like is you're getting these mutually self-reinforcing realizations that not only is this good, but that's good, and then they make each other double good, and on and on.

That's right. You say, "My God, one day this is how we're going to build all our networks." It's such a wild thought that you ask, "Am I fooling myself?"

I took out the briefing charts and went around to present this idea ... and got dumped all over. People said it wouldn't work because of this reason or that reason. I would study the problem and come back. A good wire-brushing like this was necessary. You see, these ideas were crazy. We were in an analog world. The image of a computer was a great big room with parts failing all the time. I said, "You can build computers in shoe box size. It's already happening on board airplanes."

Do you make any attempts to demo any of this?

No. Rand jokingly referred to itself as standing for "research and *no* development." I've since learned that it's a hell of a lot easier to just build something than to try to convince somebody who doesn't believe it's possible.

So, it wasn't a demo environment there.

No. Hey, this was not our business. We wanted the telephone company to do it. [*Cackles ruefully.*] The Air Force said to AT&T, "Look, we'll give you the money. Just do it." AT&T replied, "It's not going to work. And furthermore, we're not going into competition with ourselves."

How seriously did AT&T look at the proposal?

The response was most interesting. The story I tell is of the time I went over to AT&T headquarters - one of many, many times - and there's a group of old graybeards. I start describing how this works. One stops me and says, "Wait a minute, son. Are you trying to tell us that you open the switch up in the middle of the conversation?" I say, "Yes." His eyeballs roll as he looks at his associates and shakes his head. We just weren't on the same wavelength.

If you think in analog terms, the signal arrives instantaneously. If you think in digital terms, time moves very, very slowly, and you can do things like change the path while you're in the middle of a syllable. But it was a mental block. They didn't understand digital. It was mostly generational, but there were young analog guys who had the same problem. If a guy considered the model of transmission to be analog, transmission time was instantaneous. It was a hang-up that caused people to think I was bullshitting them or didn't know what I was talking about.

But couldn't they find out if you knew what you were talking about pretty quickly?

They said, "Oh, the people at Bell Labs are not practical. They don't understand telephony." That was the sort of response I always got. It was, if you'll pardon the expression, a paradigm switch. It was very hard for them to believe something like packet switching could be done.

In retrospect, it looks like AT&T not only behaved badly in terms of blinding themselves to what could be significant innovation, they also behaved stupidly in setting their company on a path of aversion to the world that was going to replace them. And Bell Labs, which should've been used as a way to prevent them from making that kind of mistake, wasn't.

Bell Labs really did try to change things. I had set up a meeting with Ed David, the executive director of Bell Labs, and his equivalent, the chief engineer of the telephone company, at Ed David's house. I'd explain something to Ed, who was a digital type and understood it. He'd turn around and explain it to the AT&T man, almost in Western Electric [18](#) part numbers. Then the analog guy would say something in Western Electric part numbers, and David would translate it to me. It was an attempt - a strong attempt - to try to cross that bridge, that somewhat intellectual, somewhat emotional bridge. They're the people who could've and should've done it. But the company was controlled by people who had been there a long time, and they were all analog. They weren't even switching people.

So the Air Force wanted to build a digital packet-switching network, but AT&T refused. What happened next?

Rand, in 1965, issued a formal recommendation to the Air Force to proceed without AT&T. The Air Force set up a committee to check it out. They concluded yes, it would work, it was technically

feasible. They felt the cost would be a little bit higher, but not significantly higher. The costs were a drop in the bucket to what we were already spending. The system could pay for itself in no time.

Everything was going smoothly until the Department of Defense said, "Oops. Under the Defense Reorganization Act of 1949, this activity belongs with the Defense Communications Agency."

A little history on the DCA: Each of the services was highly competitive, and each was building its own communications system.

I was in the Army.

So you know who the enemy was - it was the other services. To overcome the competition and duplication among them, the Department of Defense pulled the communications functions out of the individual services and put them in a single new agency, the Defense Communications Agency.

All the services were building their own message switching systems: electronic versions of the torn-tape teletype systems. The committee went around and said, "We can't afford all this crap." The family units couldn't even speak to one another, so we didn't get any redundancy out of it. Their recommendation was to pick one and shoot the rest, amid the screams.

But at the time, DCA was still old analog people. I'd worked with them in '61 and '62. I realized that if DCA tried to build the system, it wouldn't work. It would be an utter waste of taxpayer money. Around early '66, I said, "Oops, tilt!" I spoke to my friend Frank Eldridge, who had worked at Rand and was working on command and control survivability before I got there. We were very close and he was a very strong supporter. I said, "Frank, it ain't gonna work." So the funds for it got clipped.

You were actually powerful enough at this point to pull the plug on it?

I pulled the plug on the whole baby. There was no point. I said, "Just wait until some competent agency comes around. Because if DCA gets the task, it ain't gonna work, and for the next 10 years, people will say, 'We tried that, but it didn't work.'"

Let's put this in the Cold War context: The idea was to have basically retaliatory capabilities, so you wouldn't have to use them. But that only works if the other guy knows about it. What was going on in terms of visibility? Were you sending your papers to the Soviet Union?

We kept everything open that we could.

And trailed it in front of known spies?

We *published* it! I gave a course on it at the University of Michigan in '65. We were a hell of a lot better off if the Soviets had a better command and control system. Their command and control system was even worse than ours.

That sounds pretty enlightened. This was the Air Force saying, "We want the enemy to have the same second-strike capability as we do."

There's certain things you don't say. But yes.

What level did that enlightenment come from?

I think it went throughout. Those guys weren't dumb.

The president knew, the Secretary of the Air Force knew? All these people thought, "This is not a secret we want to keep"?

It didn't ever get up to that level, I don't think, but it permeated the question of "Do we keep it secret or not?" Right from the beginning, the answer was no. At Rand we had secret documents, but the secret documents pertained to vulnerabilities and specific things like that. Some issues in crypto. But our whole plan, the concept of packet switching and all the details, was wide open. Not only did Rand publish it, they sent it to all the repository laboratories around the world.

Since the Soviets were presumably able to know about what you were proposing, is it possible they were developing good command and control for a second-strike capability?

I don't know what was going on there at the time. But they didn't have the digital technology. They were so far behind.

Yet they could believe that we had second-strike capability because of this?

Yeah. Their approach would be different.

Still, in '66 it was no-go. You had shut down the plan with the Defense Communications Agency. Were you disappointed?

No. The military pressure for it was diminished. The ideas had gotten out.

So, a back burner for packet switching. You worked on other things, presumably?

Yeah, I was working on computer privacy. I was the first guy to testify to Congress on the problem. That and a lot of other things.

Do you ever wish you owned a patent on packet switching?

No. First of all, 17 years went by very quickly. Secondly, it would've gotten in the way of people using it. That was one of the objectives: to broaden the access.

What's your sense of when you first thought that this thing you were working on was going to take over the world?

Around December '66, I presented a paper at the American Marketing Association called "Marketing in the Year 2000." I didn't talk about packet switching, but I described push-and-pull communications and how we're going to do our shopping via a television set and a virtual department store. If you want to buy a drill, you click on Hardware and that shows Tools and you click on that and go deeper. In the end, if you have two drills you're interested in, then you hit your Consumers Union button, and their evaluation goes up on the screen. Pretty much what WebTV is. Some in the audience were furious. They said, "People don't go shopping to buy things. They go there because of the enjoyment. You don't understand women." I could see a few people going for it, but most of them were shaking their heads.

In 1966 you were foreseeing the way networks would be distributed, and you were starting to see applications. What stuff that emerged from '66 to the present surprised you?

Playing with the Arpanet as a user, fairly early on. The number of users was very small, but the rate of increase made it obvious what was going to happen. It was just a matter of time. No one is ever as shocked and surprised as when the inevitable occurs.

1 Robert W. Taylor (b. 1932) Former deputy director of the Information Processing Techniques Office of the Advanced Research Projects Agency (now Darpa), who in 1966 proposed a network to connect research computers at different sites across the US.

2 Donald Davies (1924-2000) Researcher at the British National Physical Laboratory credited with creating packet switching architecture in 1965, coining the term, and presenting the idea in 1967 to US researchers who successfully proposed it as the data transfer model for the Arpanet.

3 Packet switching The rapid transmission of small blocks of data over a channel dedicated to the connection only for the duration of one packet's transmission. Each packet can take a different path from sender to receiver. By contrast, most telephone systems still use a circuit switching model, in which all data travels along a continuous dedicated path between the sender and receiver.

4 Rand Corporation A nonprofit institution founded after World War II to guide public policy through the research and analysis of issues from national defense to criminal justice. The name is short for "research and development."

5 Minuteman The US's mainstay intercontinental ballistic missile, this solid-state model was first deployed in 1962. The proposed National Missile Defense (NMD) program would be based on retrofitted Minuteman III missiles, which are scheduled to remain in service until 2020.

6 Hughes Aircraft Defense contracting giant founded by Howard Hughes in 1932 and acquired by General Motors in 1987.

7 SAGE The world's largest computer in 1958, Semi-Automatic Ground Environment was faster than human operators at monitoring radar blips to watch for attacking Soviet supersonic bombers.

8 Solid-state rocket A rocket that stores propellant inside the engine as a rubberlike substance, to allow a quick launch.

9 Bomb Damage Effect Computer Rand's 1958 calculator for estimating the impact of a nuclear blast.

10 Warren McCulloch (1898-1969) Neurobiologist whose 1943 paper with statistician Walter Pitts explored the concept of neural networks.

11 Ionosphere Region of the atmosphere (30 to 250 miles above the surface) where ionization caused by incoming solar radiation refracts high-frequency radio waves. Signals bouncing from sky to Earth and back again can travel great distances, following the planet's curvature.

12 Ground wave A low-frequency radio wave that travels along Earth, following its curvature instead of reflecting off the ionosphere.

13 Amplitude modulation A method of radio transmission in which sound is encoded by varying the strength of the broadcast signal.

14 Frequency modulation A method of radio transmission in which sound is encoded by varying the wavelength of the broadcast signal.

15 Pulse code modulation The most commonly used method for encoding digital audio onto a signal.

16 Message switching Better known as "store and forward," a communications model that's somewhere between circuit switching and packet switching. A complete message is received before it's passed on to the next node.

17 Logical address Also called "virtual address," a nonphysical address used to access a device on the network. The logical address does correspond to a physical address, but it can be remapped from one physical address to another, as necessary.

18 Western Electric Exclusive equipment manufacturer for Bell Telephone from 1882 through the monopoly's breakup in 1984.

Stewart Brand (sb@gbn.org) is cofounder of Global Business Network and author of The Clock of the Long Now : Time and Responsibility. In 1961, he was on active duty as an officer in the US Army.

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